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Quantum Cognition – Quantum Analogy

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Attempts to apply the apparatus of quantum mechanics to cognition and language have met, understandably, with a degree of scepticism within the disciplines concerned, but they nevertheless have the potential for opening exciting new perspectives. In this article, I address the question as to what it is exactly about these attempts that has drawn such attention – both positive and negative – in recent years. I shall argue for distinguishing those aspects of quantum cognition that do warrant serious consideration by cognitive psychologists and linguists irrespective of the exact nature of its relationship to classical quantum mechanics. The key lies in the important role played by analogy in both disciplines.

1. Introduction: the Power of Analogy

In recent years, attempts have been made to extend the application of the formal apparatus of quantum mechanics – developed so successfully for the sub-atomic particle world – to the macro-level world, not only to such practical phenomena as lasers and superconductors but also to cognition, language, and consciousness itself. These approaches range from seeing the literal involvement of quantum mechanics (or quantum field theory) in the macroscopic world of cognition, following Penrose (1989) (cf. Vitiello 2001), to regarding the quantum level as merely supplying a useful analogy to cognition – useful in so far as it introduces mathematical tools that can supplement those already used by experimental psychologists in order to explain paradoxical findings. Sceptical voices, for instance Scott (1995, 71), have been raised concerning all such enterprises while others have remained agnostic, awaiting further evidence.

The problem with literal approaches is that, despite intensive searches for quantum effects in 'microtubules' within brain cells relevant to cognition, none have to date been convincingly demonstrated.[1] As Tegmark (2000) has argued, such effects are far too short-lived to have an effect at the macro-level anyway. A less radical kind

1. But see Vitiello (2001, 139) for the apparent effect on neuronal microtubules of cognition-affecting drugs.

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of approach is represented by the research programme of Quantum Cognition. Areas this has been applied to include: decision processes; ambiguous perception; semantic networks; probability judgements; order effects of cognitive measurements; and memory (cf. Wang *et al*. 2013 for an overview with copious references). As Wang *et al*. (2013, 678–679) point out, Bohr's original formulation of complementarity (referring to the ambiguity of the particle/wave distinction) actually had its roots in psychology – coined by William James. It was Edgar Rubin, a Danish Gestalt psychologist, who acquainted Bohr with the idea. Complementarity in the broadest sense refers to descriptions that mutually exclude each other but are jointly necessary to describe a situation exhaustively. Bohr himself was convinced throughout his life that quantum theory has its applications in the macro-world of psychology and philosophy (Bohr 1958).

The position I shall myself take on the relationship is similar to the 'analogy' perspective of Quantum Cognition, but also incorporates Scott's view of successive, sustained stages in the emergence of Mind. Analogy is a powerful factor in human cognition, as Itkonen (2005) has illustrated in great detail. An anonymous reviewer has pointed out that any prose exposition of quantum mechanics is itself in fact analogical in nature. The kind of analogy that Quantum Cognition is mainly concerned with is of the dynamic kind that Itkonen describes at work behind inference processes such as abduction. I shall have little to say about the formal mathematical extension of quantum probability theory to the macroscopic world – I am a mathematically naïve realist who believes that the analogy itself is sufficient to throw at least some light on the 'mysteries' of brain function and cognition. If the mathematics can produce valid results (as is apparently the case) then so much the better. I am particularly interested in the relevance of this perspective for the mental lexicon, but I shall also venture into the bearing that it has on the way the brain balances entropy and 'negentropy'. This article is thus a further exploration of the ideas dealt with in a recent book concerning abstraction, projection, similarity, and entropy in relation to cognition (Fortescue 2017). Central to these considerations are the notions of holism, context and the discreteness of levels as applied to rational thought, dreaming and imagination. In the conclusion I shall tackle the question as to *why* the particular analogical relationship between cognition and the quantum mechanical world should be as compelling as it is, though I shall also pinpoint certain shortcomings.

2. The Source and Target of the Analogy: Some Quantum Mechanical Principles Applied to Cognition

A cardinal notion in quantum mechanics (QM) is that the individual sub-atomic particle (definable as a wave function) consists not of a 'thing' but of the superposition of incompatible states above a ground state, separated according to a universal constant of energy (Planck's constant). This is also what keeps the electrons of atoms exclusively on discrete 'shells', with no intermediate position between them when they shift up or down in energy level (a picture originally due to Bohr). The constant

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ensures that the superposed states remain discrete until activated or 'measured' by being subjected to a measuring context, thus causing their collapse or 'decoherence' to just one state detectible at the macro-level. Moreover, the exact position of such a particle cannot be determined simultaneously with its momentum (Heisenberg's 'uncertainty principle'). Any specific frame of measurement thus changes the features of the 'object' being measured (this at least is the standard 'Copenhagen' interpretation of Niels Bohr and colleagues).

The quantum world is holistic, probabilistic and dynamic: particles cannot in principle be isolated from their context, which is the 'field' in which they are embedded (cf. Rovelli's relational interpretation of quantum theory – Rovelli 2021). Massive particles (or 'fermions'), such as protons, presuppose massless 'particles' ('bosons', such as photons) that form the field in which they exist and determine their relations with other fermions. Bosons can convey information across whole populations of fermions such that state changes can spread quasi-instantaneously through a structured nexus of particles by 'phase transitions' or 'symmetry breaking' from a relatively stable ground state (manifest at the macro-level in, for example, crystallization phenomena). All particles display wave-like properties (as in the famous 'two slit' experiment in which a stream of photons displays diffraction and interference effects when travelling through two different slits in a screen). Since there is only a *probability* of a particle being in one place, they can be envisaged as diffusely spread around a core of maximal probability – they may be in more than one place at once, dispersively, in the sense that their various states have differing location probabilities until measured (hence the possibility of 'quantum tunnelling'). This can be described mathematically in terms of multi-dimensional Hilbert (or 'vector') spaces. 'Spooky' – i.e. non-causal, non-linear – action-at-a-distance (as in Einstein *et al.* 1935) is possible since changes to the state of a particle (in measuring events) collapse the whole wave function, not just the particle's more densely probable spatial core. 'Non-linear' is used here in the general sense of 'the whole being more than the sum of its parts', but also implies 'non-predictable' except as a probability. 'Entanglement' or 'interference' between separated states is allowed: quantum entanglement means that multiple particles may be linked together in such a way that the measurement of one particle's quantum state determines the possible quantum states of the other particles even at huge distances of ensuing separation. Dynamic processes of interaction between individual particles are time-independent – they can equally occur 'in reverse'.

It should be pointed out that according to some theoreticians, the role of the observer in wave function decoherence has been overstated. For a start, it is the whole measurement context, including the apparatus that is supposed to determine this, but beyond this others (including, influentially, Penrose) see spontaneous 'objective reduction' as possible (if rare), and wave function collapse taking place independently of any observer when 'Planck's length' separating states is exceeded owing to space/time curvature.

Having listed these well-known quantum mechanical features, let us see how they might – purely by analogy – be reflected on the macro-level of brain and cognition.

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How might they be correlated with what is known of brain structure and function?[2] Consider a memory trace, say of a word and its meaning, embodied in a neural network linking various spatially dispersed neural assemblies via associative links between them. We can envisage various states of the network depending on context (in the broadest sense). Let us replace the QM notion of 'measurement' with 'activation from without', setting the word in a specific context. What happens is analogous to 'wave function collapse' at the micro-level. Moreover, such a collapse is not to an infinitely gradable state but to one of a number (perhaps a great number) of individual states, albeit some of which may be 'entangled' (non-causally, non-locally associated), each state constituting in fact a different – though related – neural network, or at least a different state of the same network. The memory trace of the word plus its meaning is indeterminate in so far as it is always evolving, dependent on ever-changing contexts – the semantic space in which it is embedded is multi-dimensional and characterized by potentiality rather than manifest content. It will nevertheless have a context-free 'ground' or 'rest' state which can be defined in terms of the conjunction of stable phonological and semantic features, free from any specific context. What is activated in a case like this is not just excitation that spreads out gradually from a specific node of the network – say the phonological form of the word – to neighbouring cortical regions, as is often assumed in neural network modelling: the activation is also transmitted at relatively high speed to areas of the cortex far removed from the phonological representation via white matter axon bundles. It sets off cascades of activity with both spatial and temporal ('spike train') dimensions. A widely distributed field is activated that can be described as a multi-dimensional Hilbert space of the sort used to describe sub-atomic phenomena. And the activation event, by placing the word in a specific context (or nested set of contexts), perhaps never experienced exactly before, will change the nature of the memory trace itself, however slightly. This is not precisely 'quantum tunnelling' of course, but it does involve rapid long-distance dispersion of activation by the propagation of non-linear (non-dissipative) bursts of chemical reactions along myelinated axons.

Finally, all elementary particles of a certain type are identical (though they cannot be in the same location with the same momentum at the same time) yet in combination they can produce unpredictable emergent (e.g. chemical) properties. Similarly, individual neurons of a certain type are for all intents and purposes identical (in general internal structure), but within Hebbian neural assemblies – and assemblies of assemblies requiring activation by lower level assemblies – they can produce emergent properties and functions in cognition, ultimately (let us assume) resulting in conscious experience. What cannot happen at the macro-level, is of course the analogue of quantum level time-reversal, although a bi-directional activation relationship between different parts or levels of a specific memory trace network is normal.

One cardinal aspect of quantum theory that I shall focus upon in the following sections is the discrete nature of states superposed above a ground state, individually activated according to the nature and strength of the input (analogous to

2. See Arbib *et al.* (1998) for a detailed description of brain structure and function.

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measurement events). Memory traces are incorporated in discrete neural networks, albeit networks that are constantly being modified by new activation and which are subject to interference phenomena. What reaches consciousness in working memory is, essentially, one percept or concept – or one whole propositional thought – at a time. The means whereby this input is 'gated' is roughly understood today. Thus, Pulvermüller (2002, 80ff) describes the involvement of the basal ganglia in the singling out and amplification of individual networks from a multitude of potentially activated ones by a specific interplay of positive and negative reinforcement and inhibition. This complex circuitry allows for more specific top-down control by the cortex as to what is entertained in working memory (whether in the form of inner speech or perceptually based imagery). But if any given memory trace (embodied in single neural assemblies or whole networks) has multiple potential states, this 'gating' of input will have to do more than activate the given trace, it must also 'collapse' the possible range of activation states to just one in accordance with the context, much as happens with wave function decoherence at the micro-level. What stops the network from collapsing permanently (with concomitant loss of information) is precisely the discreteness of the contexts that hold the superposition of states apart until collapsed, as if by some analogue of Planck's constant. Although this could hardly be deemed 'constant' in the QM sense, the memory traces of specific activating context types will themselves be isolatable by the kind of mechanism Pulvermüller describes, which may indeed have a minimal limit to its discriminations. With the accumulation of experience, these contextually defined distinctions will become more and more fine-grained, but nevertheless remain separate: they represent discrete states of the 'same' or overlapping networks which require specific contextual inputs (and strengths) in order to be activated.

What can be expected from such an organization is spontaneous shifts from one state to another, without intermediary fuzziness. This phenomenon is perhaps better illustrated in successive dream imagery than in waking thought processes, which are 'clamped' by persisting environmental and intentional context. What is common to both is the role of analogy (the recognition of similitude), which affords rapid shifts of attention, essential in waking life for reacting to danger, for example. In dreams, time can be speeded up, slowed down, curtailed by bird's-eye summaries, or proceed by drawing in more or less randomly generated imagery to parallel the structure of experiential problems and speculations from conscious life (by unconscious analogy, as it were). There is more interference from 'similar' things and events in dreaming than in waking thought and therefore greater entropy, less 'useful order'.

As regards conscious, rational thought, it is obvious that deduction (as in 'modus ponens') involves discrete steps, but this is also true of induction (generalization from discrete instances), and abduction (forming a hypothesis by imaginative blending of abstracted schemas, then testing the match with instances). The discrete steps may or may not be jumped over by experience-based intuitions (by 'natural' inference – another analogue of 'quantum tunnelling'?). If such quantum-like leaps were not possible, muddled thinking and ambiguous physical reactions would be the result.

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As it is, rational thought reduces entropy (disorder), a matter I shall return to in the final section.

But let us take a step back from active thinking and consider sensory input and its effect on episodic memory. As described in Fortescue (2017), the target of analysis-by-abstraction of sensory input is its matching with stored experience (whether in strictly context-bound episodic memory or more allocentric semantic memory). When the match with memory traces already laid-down is more or less exact (more or less because the context will always be slightly different) rather little will happen, but what differences there are will contribute to fine-tuning the trace – say the meaning of a word or the content of a particular type of sensory or social event. Abstracting and registering 'differences' in multi-sensory inputs in the process of creating new memories (and sending them 'upstream') appears to be a principal function of the hippocampus.[3] In more permanent memory traces in the cortex it is reasonable to suppose that some form of 'averaging out' of instantiations will occur, eventually forming summated prototypes – underpinning the transition from accumulated instances to generalized 'schemas'. This is another kind of 'collapse' to a 'ground state', one that can be reversed. Note that ground states require minimal energy to maintain (they reflect rest state homeostasis), but are subject to continual destabilization according to the activity of elements elsewhere in the network(s) that they are involved in. Collapse from a given state isn't necessarily all the way to the ground state, but to any of the other states (depending on specific contextual conditions), thus affording associations to other related networks. The 'averaging out' involved, one could argue, is part and parcel of concept formation and extension, and, as regards language, to the appearance of superordinate semantic categories, guided by external, socially determined feedback.

But prototypes and image schemas are notoriously 'fuzzy' – so where is the quantum discreteness here? The brain has both 'analogue' and 'digital' functions – the former for example in recognizing 'best fit' similarities of input or in keeping track of movement through a landscape, the latter in recognizing specific distinguishing features. Only the latter would appear to be 'quantized'. And what of 'blends' (as in imagining new combinations of concepts) and 'morphing' between otherwise discrete images (as in dreams)? This is where the notion of quantum 'entanglement' may become relevant. One can regard a phonological word (or some other kind of 'perceptual symbol' – cf. Barsalou 1999) as a tag to a memory network functioning as a discrete point of access. Such a 'tag' is presumably anchored in a neural assembly in Wernicke's area of the cortex (a tightly knit column consisting of a number of individual neurons), which is itself liable to contextual variation (e.g. by speed and pitch). The most proximate connections from one assembly to its neighbours may be

3. This crucial part of the limbic system responsible for episodic memory takes input from numerous sensory and emotional parts of the brain and consolidates them (with the involvement of its inherent theta wave oscillations) as holistic events that will be passed on in turn to the cortex for storage, gradually modifying the cortex but more immediately looping back on itself through other parts of the limbic system. The direction of information flow through it can be reversed, acting thus as the brain's 'librarian' or 'search engine' (Buzsaki 2011, 285ff).

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inhibitive rather than excitatory, although related assemblies (e.g. in clustered word 'families') are probably in local proximity by positive associative links as well. But the meaning associated with a phonological word is diffusely extended across cortical regions much as the precise location of a quantum particle is diffuse. Fields may overlap and produce interference effects both at the micro- and macro-levels. Individual neural columns can participate in numerous different networks according to broader context-dependent input. Compare the gating role of complex dendritic trees of pyramid neurons, perhaps acting as similarity detectors. This does not mean that the possible context-dependent states of a particle – or of a word's meaning – are not discrete. The same applies to perceptual images: undergoing constant gradual fine-tuning and being open to interference from other images and biases does not mean that the different states of imagistic memory traces are not themselves discrete, in accordance with contextual factors. This discreteness can be spatial or temporal, thus the environment can be 'moved through' and pictures 'read' but also here discrete jumps are involved at a neurological level too fast to register consciously, i.e. in the continual saccades of eye movements.

As regards memory storage in the cortex in general, the 'reservoir' models of Singer (2013) and others are directly premised on the notion of the superposition of multiple memory states at different frequency bands. The ground state of the neural assemblies in which memory traces are embodied in these models is oscillatory in nature. The multi-dimensional superposed states are taken as collapsing into unitary outputs by the intervention of a 'readout classifier' according to context, task, or intentions, etc. This could well involve the pre-frontal lobes, which furthermore function as a general recognizer of analogy relations across modes. An important role may also be played by inhibitory 'basket' cells countering the potential propagation of axon responses, just as atoms and molecules are held together in dynamic balance by opposing elementary forces.

Quantum Cognition can, in sum, be seen as an attempt to formalize the manipulation of information and value by the brain (especially in the area of decision-making). It employs the mathematical apparatus developed within QM with its probability distributions and 'complex' numbers capable of modelling higher dimensional spaces. At the same time, it distances itself from claims about the direct involvement of the sub-atomic micro-level in cognition. Analogy and non-compositional holism is central to this approach and its relation to Gestalt perception theory as well as quantum theory has not gone unrecognized.

3. Relevance to Language and the Mental Lexicon

Quantum Cognition has been applied to language. Bruza *et al.* (2009), for example, have suggested in a series of experiments that certain paradoxical results in word recall tests involving the 'dispersive' activation of targets via cue words is explicable – and can be represented mathematically – by the quantum theory analogy. They describe their application of this theory to the mental lexicon as a 'quantum

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metaphor model'. Their results indicate the collapse of multiple word meanings by a contextual cue (a prime) affecting the relevant network space as a whole. For instance, the collapse of 'bat' to its specific animal sense by a suitable prime can influence the collapse of 'boxer' to *its* animal sense in an immediately ensuing test if they are 'entangled at a distance'. Words are seen as superimposed states within a multi-dimensional Hilbert space and not just as deterministic units functioning by 'activation spreading'. Primes affect the target word's network much like the effects of measurement in a quantum system. Additional associative links en route to the target may be additive, facilitating rather than slowing down access to it despite increased distance, reminiscent of 'spooky' at-a-distance quantum effects.

Brainerd *et al.* (2013) have conducted experiments supporting a 'quantum superposition' model of otherwise incompatible ('over-distributed') episodic states. They were concerned with the paradoxical 'yes' responses of subjects to false (but semantically related) cues in word recall tasks, e.g. being presented with 'Sprite' or 'Fanta' when the actual target presented was 'Coke'. This they explain in terms of access to superordinate 'gist' categories forming alternative higher states of the target words, recalled 'as if' equivalent to the 'ground' state of the target word itself. The cue (whether 'true' or only indirectly relevant) causes the multiple states of the target word to collapse to the one on which the judgement is based – they refer to the experimental setup as a 'word slit' analogy to the 'two slit' photon experiment.

I have already mentioned the prototype nature of concepts. How exactly might this reflect anything analogous at the quantum level? Take for example the concept 'bird' (i.e. the average English adult's associations with that word). Numerous acquisitional studies have illustrated how children learn the meaning of such words through early instances, specific birds (toys or real creatures) to which they hear adults apply the term – they thus under-extend their use of the word (see Tomasello 2003 for the usage-based theory of language acquisition). Their usage is then typically over-extended in various ways (say to toys of a similar material or shape by an analogy along one perceptual dimension or another), until increased exposure to 'correct' adult usage (aided, say, by pictures in story books) gradually hones it down to approximate that usage. The result will be a concept displaying 'prototype' properties, the most typical instances of the category being the type of specific bird to which the child has been most exposed in his or her given environment – say a blackbird, or perhaps a sparrow as regards English children. But subordinate types (say the hyponym 'blackbird') will themselves be formed through the accretion of instances which combine specific values of certain general features of the hypernym (like colour or size). Thus, concept formation can best be seen as involving both 'bottom up' and 'top down' processes. In Fortescue (2009, 15 and 71) this is discussed in terms of the memory network for 'parrot' in relation to that for 'bird'. In both the hyponym and hypernym cases the superposition and averaging out of instances appears to be a central process involving the abstraction of particular distinguishing features (affective as well as sensory) from instances, starting no doubt at a pre-linguistic stage. Recognition of similarities is the driving force behind further abstraction of higher order abstractions in general (e.g. of the category 'animal' covering both cats and

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horses). The clear hypernym–hyponym relationship, however, will arguably emerge only with the acquisition of phonological 'tags', i.e. names for things, and this underlines the importance of language in helping keep distinct concepts apart without gradual 'collapses' back to earlier stages. In other words, the tendency of similar inputs to memory to become 'averaged out' (i.e. absorbed into existing concepts just as repetitive experiences may be absorbed in episodic memory), may be counterbalanced by the registering of relevant differences and 'tagging' them by a word or phrase. The result will be tagged concepts embodied in overlapping or nested memory traces (networks of neural assemblies) susceptible to activation in different states according to specific context, much as different contexts of 'measurement' in the quantum world cause the collapse of complex wave functions to one potential state or another.

Aerts *et al*. (2013) discuss prototype theory precisely in terms of the quantum notion of ground state (the prototype), with higher excitation states corresponding to more specific exemplars according to context. Thus, they discuss the paradoxical fact that people tend to regard a 'guppy' as a typical 'pet fish' (in America at least) although its 'typicality value' is not high for either 'pet' or 'fish'. This seemingly irrational judgement they explain in terms of the effect of the conjunct notion 'Pet-Fish' which introduces (as if by quantum 'measurement') the context 'Fish' into the 'Pet' concept, in which case the ground state (prototype) of 'Pet' is changed into a new state 'Pet-fish'. The typicality of 'Guppy' will be different depending on the state, and hence the high typicality of 'Guppy' in the state 'Pet-fish' of 'Pet' and its lower typicality in the ground state of 'Pet'.

The same authors (Aerts *et al*. 2013, 751) also discuss the 'collapse' of superordinate conceptual states such as 'an animal acts' to more concrete subordinate ones such as 'a horse whinnies', which is highly reminiscent of Construction Grammar under the general umbrella of Cognitive Linguistics (cf. Goldberg 1995). One of the key features of the latter is the hierarchical relationship between generalized construction types, e.g. 'X V-d Y Adj' (itself an instance of 'CLAUSE'), and instances of the types with the variables given specific linguistic values, such as 'John found the film interesting' or 'She wiped the glass dry', or still more specifically, 'The saucy barmaid wiped the dirty beer mugs dry' (which further integrates the typical noun phrase construction). The relation of superordinate to subordinate constructions here involves structural transference from level to level. The relevant point is that these construction levels are discrete, not fuzzy.

Point-to-point correspondences are also a feature of 'Blending Theory' within Cognitive Linguistics. This developed in order, amongst other things, to explain counterfactuals and novel combinations of words such as 'land yacht' (referring to a luxurious automobile) in terms of input and resultant 'mental spaces' (cf. Fauconnier and Turner 2002, 357). Usually the 'base' space is present reality, while further related spaces may be purely hypothetical. Such blends combine the relational structure of its constituents in higher schemata. Some of these are fleeting and *ad hoc* – as are the blends produced in dreaming. Others persist as conventional expressions within the language, such as the example of 'shoulder strap' analysed in Fortescue (2009, 79) in terms of alternative 'scenarios' (contexts) – e.g. the support

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for a rifle or for items of female apparel. The 'ground states' involved here are the meanings of 'shoulder' and 'strap' out of context, with higher level interpretations of 'strap' emerging from the specific contexts relevant to those states. The defining features of its ground state are reflected point-for-point (although modified) in the two contextualized interpretations, which would collapse again to the ground state meanings of the component words if the combination were not in fact conventionally lexicalized (as attested in standard dictionaries). Another similar type of relationship that has taken centre stage in Cognitive Linguistics is that of metaphorical and idiomatic expressions to their literal source. The ground state semantics of simple words such as 'go', related to a basic spatio-temporal or kinetic 'image schema', may be extended to higher, more abstract domains ('The light went from green to red', 'Fame went to his head', etc.). All of this reminds us again of the analogy to collapsible but discrete quantum states.

It is not only in Cognitive Linguistics one finds similar relationships. Change by analogy and/or reanalysis has long played an important role in historical linguistics, and this typically takes place by discrete, rule-like quantum steps although its spread through populations is statistical/probabilistic (again reminiscent of the micro-world of QM). The same applies to grammaticalization processes, the 'gradual' change of lexical items into grammatical ones by the emergence of new 'bleached' senses (as with 'go' in 'he's going to spend the summer at home' versus 'he went home'). These may overlap in time and occasionally produce ambiguity, but this is not the same as fuzziness. In fact linguistic rules and functions in general are both quanticized and probabilistic (like all natural laws, according to Schrödinger 1944): there is no halfway house between a unit functioning as a subject or as an object of a verb, say, but the distribution of SVO (Subject, Verb, Object) order within a given language may be a matter of contextually determined probability. The parallel between probabilistic linguistic rules and quantum computing has been discussed by Skousen (2003). This can be extended even to the pragmatics of language use. Specific instances of speech acts can combine several discrete acts, each conventionally formalized, say that of stating and that of (indirectly) requesting in 'That mug needs washing'. This is analogous to quantum 'inference' or 'entanglement'. Context will, if communication is successful, collapse any potential ambiguity to a single intention (however complex).

Finally (as a bridge to the following section) a few words about 'mental models' are in order (cf. Johnson-Laird 1983). These are the structures in memory resulting from the assimilation of a coherent 'body' of input through the senses, in particular through reading a text or hearing a story. The gist of mental model theory is that the information contained in the text or story is not retained verbatim but in structures analogous to those of the 'real' perceptual world. It remains controversial as to the exact way this information is stored and how it could be possible to store in this way more abstract meanings without a clear perceptual basis. Recent approaches suggest that mental models must remain to some degree multi-modal and retain representations of at least some specific words (for names and key abstract concepts), but much will depend on context and prior experience. They may also contain a temporal dimension, unfolding in time.

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In a test situation reported in Fortescue (2007) all versions of the same story recalled by 24 subjects one hour after reading it were different, but each contained the same key elements and 'propositional' structure (analysed in terms of strong and weak 'nexus' links). Moreover, when the same subjects were asked to recall the story a week later, the results were again all rather different, curtailed further yet sometimes repeating changes of detail incorporated in their first recalled version. This suggests that what is retained is neither verbatim memory nor a purely perceptual 'model', but rather a multi-modal network anchored in higher association regions of the cortex. This may in itself be 'amodal' (or 'hidden' in connectionist terms), but will contain the potential for active projection back – through long-distance axons – to the primary sensory and language regions of the cortex to reconstruct the approximate meaning extracted in the first place. This potential will be partially degraded through interference from other overlapping memory contents that renders verbatim access difficult (though sometimes achievable), but it is likely that it is above all the new context in which recall is required that will most strongly affect the integrity of the model. Be that as it may, the bare 'skeleton' of the story is what typically remains after time has elapsed following the initial reading – its 'ground state' as it were. This can potentially be reactivated in a variety of ways and contexts (with additional 'bridging' elements from general experience making up for any lost structural coherence). The complex mental processes involved in such tasks bring us to the threshold of higher thought processes. Can we still discern analogues to quantum phenomena here?

4. Quantum Thinking and Consciousness

In order to discuss the possible relationship between Quantum theory and conscious thought in particular, we need to go beyond the 'metaphorical' stance of Quantum Cognition and consider what quantum literalists, following Penrose's lead, actually have to say on the matter. I cannot claim to comprehend all the mathematical and biochemical subtleties involved, but it will suffice, I hope, to present the gist of their position here. Vitiello (2001), representing this general line of research (of which there are many strands), emphasizes that its basis is Quantum Field Theory (QFT) rather than QM as such: just as particles and their fields in quantum theory cannot be dislocated one from the other neither can structure (brain) and function (e.g. consciousness) be separated in cognition. Memory is a dynamic system rather than one of fixed neural nets. Going much further than the Quantum Cognition analogists, Vitiello follows up Penrose's suggestion as to the possible role of microtubules in consciousness, seeing these tunnel-like filaments forming the cell body's 'cytoskeleton' as capable of mediating non-linear action-at-a-distance through 'boson condensation' on 'correlated' boson fields (recall that 'bosons', like photons, form the fields of 'fermion' particles). Sensory input breaks the ground state symmetry (stability) of such structures, producing (new) emergent symmetry of different correlated brain areas. Memory states are seen as macroscopic quantum states 'due to the coherence of correlation modes'. The laying down of memory traces takes energy

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and adds meaning/value to the system, not just information. Sensory input affecting the system creates the macroscopic 'arrow of time' and decreases its entropy since, according to QFT, ground states are ordered and constitute energy minima. In sum, consciousness arises from the collapse of the collective quantum state of microtubules, not via the computational activity of neural synapses (Vitiello 2001, 130).

Vitiello sees in the brain's environment a time-reversed 'double' of its own representations. Between the two there is constant 'dialogue'. This perspective does not deny the role of neural networks in cognition, it sees the brain rather as a mixed system – quantum dynamic and electrochemical (neural) at once. The latter, at the classical macro-level, is seen as in some sense emergent from the former. Consciousness, however, does not just emerge with the macro-level, if I understand him correctly, but displays certain properties that cannot be explained at the classical level alone – notably its non-linear holism. At the deepest level it arises out of what Bohm (1980) calls the multi-dimensional 'implicate' order in which both matter and consciousness are 'enfolded'.

Globus (2011) has applied the QFT perspective specifically to conscious inner speech. In the 'dual mode' theory that he shares with Vitiello, neither the inner 'our' or outer 'alter' modes of the universe constitute reality on their own, ontological priority lying in the 'between-two' relationship between them; the two modes share a common ground or 'vacuum' state. He characterizes the 'our' mode as entropy-increasing while the 'alter' mode is equated with 'time-reversed' negentropy. Qualia (subjective experiences) arise from the 'emergent symmetry of different brain areas' just as 'meaning' arises out of 'self-tuning' of the whole system. The lost symmetry after symmetry breaking can be returned to, thus forming the condition for two-way signifier/signified semiotics. Inner speech, reflecting the holistic origin of consciousness, has for Globus 'no extension'. For him, spoken speech and inner speech are both 'between-two', only the latter lacks the participation of auditory information, i.e. location, loudness and pitch. Tegmark on the other hand has argued that the holistic, non-localized 'feel' of consciousness does not necessitate quantum theory: thought processes are in themselves non-local excitation patterns much like ocean waves (Tegmark 2000, 4203). One might add that consciousness arising at the top of a complex mapping hierarchy is a priori unlikely to be felt as 'local'. Vitiello (2001, 136–137) does suggest a way in which internal, microtubule-based non-localization may be combined with localization – the spreading through neuronal assemblies from a 'focus' initiated by input from the environment. In dreaming, deprived of input from without, only short-lived, low-energy fragments of memory can arise, insufficient to act as focus for wide-scale spreading through the cortex as is necessary for full, sustained consciousness.[4]

Let me develop a little further the alternative, hierarchical view of the organization of cognition as the basis for consciousness. Scott, in his scenario for the

4. Dreaming can arguably be seen as the source of metaphor, with multiple levels homologous in some sense one to the next. These interacting levels range from long-term concerns to trivial details from the recent day's occurrences, often with blends or additions from earlier dreams already stored up, 'props' at hand for the semi-conscious narrator.

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emergence of mind, emphasizes the non-linear nature of biochemistry in which the whole is not the simple sum of the parts. The brain (like any organism) is organized by 'hypercycles', cycle above interacting cycle at higher and higher levels in successive 'phase transitions' from DNA all the way up to consciousness – or indeed beyond, to the supra-personal cultural level (Scott 1995, 170). The results of these transitions persist (though the highest levels may fluctuate). Harth (1993), note, would actually place the conscious Self at the 'lowest' level of perception, in primary sensory areas, by positive feedback from hierarchically higher but cognitively 'hidden' association areas. The essential notion of hierarchy, however interpreted, would appear to represent a problem for the literal application of QFT, which is essentially limited to two levels, whether in terms of the 'complementarity' of the quantum and classical levels, or of fermions versus boson fields, or of the mirror-like relationship between inner and outer aspects of reality. In fact QFT literalists all accept some form of emergence, just with a different emphasis as to what emerges from what. Probably no one would want to deny these days that macroscopic neural nets, like all of Nature, depend for their very existence on underlying quantum micro-level physics, where Planck's constant keeps superposed states from spontaneously collapsing. Nor that macro-level quantum effects do exist – I have already mentioned lasers and superconductors but there are also quantum effects proposed to be involved in basic life processes (cf. Al-Khalili and McFadden 2014). The question is whether and in what way it is necessary to evoke these to explain consciousness.

There are, after all, reasonable alternative accounts of the relationship between consciousness and the brain that go into considerable neurological detail – notably that of Damasio (2000). He distinguishes 'core' consciousness, involving the central body map and emotional system, and 'extended' consciousness, which covers essentially the contents of memory. Bohm on the other hand insists on the primacy of the sense of movement through time as the core of consciousness, and uses the analogy of music, enfolded along with concomitant emotional reactions as an approach to his hypothetical 'implicate order' (Bohm 1980, 199ff.). But Damasio's core consciousness can be aware of a narrow experiential 'moment' in which it knows itself observing movement (say that of a bird in flight), while extended consciousness places such an event in a 'broader canvas and over a longer period of time' that contains 'the lived past and anticipated future' (Damasio 2000, 192–196). His extended consciousness is thus quite capable of 'enfolding' time-extended memories (e.g. for music or speech, associating one moment-long phrase with the next) without recourse to deeper quantum theoretical explanations.[5] In the final section I shall return to the

5. A further approach to the question seems conceivable, however, namely that the bidirectional pathways associating different regions of the brain, and more especially the hippocampus with sensory and emotional areas of the cortex and amygdala, will produce interference standing waves when traveling waves of the kind described by Zhang *et al.* (2018) interact from the two directions – as in an open-ended tube. Such ephemeral, slowly decaying standing waves, an epiphenomenon above normal electrochemical neural transmission, could be the source of qualia (the subjective experience of neural activity) as they are further registered and amplified by working memory. This may be a property of all looped neural circuits, including that responsible for the core system of human language, linking Broca's and Wernicke's regions in mutual co-dependence.

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less radical perspective of Quantum Cognition and the question as to why the quantum theory analogy is a useful one even if the literal, direct involvement of Quantum theory in cognition remains dubious.

5. Quantum Cognition, Language and Entropy

Erwin Schrödinger, one of the founders of Quantum Mechanics along with Werner Heisenberg, maintained that life as such cannot be based on classical physics alone and is emergent, something completely new (Schrödinger 1944). The transition of merely physical to living matter is an instance of 'phase transition'. In particular, he described the new field of genetics as figuratively a 'quantum theory of biology' (with the caveat that quantum indeterminacy does not play any direct role in biological phenomena). Genetic mutations occur by quantum-like leaps, with no intermediate states. He further emphasized – in the context of discussing the reason why bodies have to be so large (in order to extract stable information from the environment) – the statistical nature of both the laws of physics and of cognition. This is essential for biological systems to 'average out' the randomness of movement to which individual particles at the micro-level are subject. Now indeterminacy at the quantum level is not quite the same as indeterminacy (constrained 'chaos') at the macroscopic level – for example in weather phenomena or the 'chance' intervention of factors affecting decisions. The former concerns the location and momentum of any particle anywhere, any time, and allows bizarre 'entanglement-at-a-distance' phenomena with (arguably) no direct manifestation on the macro-level. Nevertheless, phenomena on both levels may be non-linear – the relationship of the genome to the phenotype (the individual body) it produces is a case in point, involving as it does the hierarchical intermediary of superordinate 'polygenes' as well as active interaction with the environment.

Now non-linearity is related to entropy. Without going into mathematically sophisticated matters of hidden attractors in complex self-organizing systems, this can be simply put thus: the emergence of life out of inanimate matter and of cognition out of living matter, all such 'phase transitions' being non-linear, represents an increase in negative entropy, i.e. of greater 'useful order'. How do considerations of entropy apply to the brain and its functioning? The maintenance and where possible the increase of 'negentropy' in the face of the universal 'running down' of the physical universe through the inexorable working of the Second Law of Thermodynamics in closed systems is the essential characteristic of all life, but it is possible to go further and elucidate ways in which the counterbalancing of entropy by negentropy can be seen specifically at work in the individual human brain.

I have already suggested that language – words – serve to reduce the entropy of the memory system by preventing the 'collapse' of similar perceptual and conceptual memory traces and maintaining hypernym/hyponym (or superordinate/subordinate) relations essential to rational thought. More generally, the formation of higher order,

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more abstract categories from more basic, concrete ones, while requiring energy (and motivation to deploy that energy), serves to reduce the overall entropy of the brain. Increasing the mental lexicon increases the number of useful distinctions for working memory to work with. This may be further related to the distinction between the more active, volitional activity of the anterior parts of the brain (the frontal lobes), where rational thinking involves discrete logical steps, as opposed to the more passive posterior regions in which semantic memory is concentrated (as well as the primary sensory areas). It is principally through frontal lobe activity that these distinctions are utilized in coping with a continually changing environment, the brain's overall negentropy counteracting useless dissipation of energy into the environment (increasing entropy).

The brain is always on the lookout for patterns it recognizes from its environment, abstracting new ones where it can (by similarity). It abhors the random, the unexplained. It is only through analogy with what we know already that we can comprehend anything novel in our environment. This would seem to apply a fortiori to understanding our own inner nature. It is not by chance that both Bohr and Bohm appeal to analogy so often to convey their non-classical views of the universe beyond the reach of our senses.

Let me now sum things up by returning to the question posed in the Introduction, as to why the quantum analogy to cognition is as compelling as it is. We have seen, as Schrödinger convincingly argued, that cognition is both probabilistic *and* discrete, much as phenomena at the quantum micro-level are. This may be the principal reason – along with the relevance of entropy and non-linearity to both levels – why it has been plausible to apply the abstract mathematical tools devised for the quantum world to the macro-world of cognition, despite the obvious differences in content of the two levels. It must be acknowledged, however, that the analogy at the heart of Quantum Cognition has its limitations: it is not well equipped to deal with the hierarchical organization of cognition (as described by Scott), with continual, sustained emergence rather than temporally discrete phase transitions. Nor is it relevant to analysing the intentional chaining of thought whereby multiple levels and models of experience, persisting from the accumulated personal past, guide the progression from thought to thought or proposition to proposition in an associative or quasi-logical manner. These aspects of cognition – in particular those concerned with language – do not sit well with the quantum analogy, belonging squarely as they do to the classical, macroscopic level.

The brain is geared to operate with analogy, and analogy it shall always find. Nevertheless, the analogy with which this article is concerned does have its own particular utility: it encourages us to steer our investigations of cognition in the direction of correlative relationships and processes relevant to all levels of reality. These include the genetic level, where genes never work in isolation; the neurological, where the activation of specific neural micro-circuits is probabilistic; and the linguistic, where meaning is in large part contextually determined.

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